Hydrobiologia (2008) 598:409–415
DOI 10.1007/s10750-007-9159-1

SHORT RESEARCH NOTE

Extreme hydrologic banding in a large-river Floodplain, California, U.S.A.

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Received: 21 February 2007 / Revised: 28 August 2007 / Accepted: 10 September 2007 / Published online: 2 October 2007

Abstract Where tributaries meet, certain conditions of flow and topography often result in incomplete mixing and the formation of spatially and temporally persistent plumes or bands. Yolo Bypass, the primary floodplain of the lower Sacramento River (California, USA), provides an extreme example of this effect. Inspection of recent and historical aerial photographs revealed that the four major tributaries of Yolo Bypass typically do not substantially mix laterally within the floodplain. The phenomenon is notable in the number of tributaries involved (4), the distance over which the bands remain distinct (>61 km), and the persistence of the bands despite channel constrictions and long cross-wind fetch. This effect demonstrates the importance of lateral variability during floodplain flow events, including transport and distribution of chemical constituents, and habitat for fish and other organisms that use floodplains as migration corridors and rearing areas.

Keywords Hydrologic banding · Transport and mixing · Floodplain · Yolo Bypass · Sacramento River · San Francisco Estuary

Handling editor: S. M. Thomaz

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Introduction

In flowing water bodies, mixing is a function of lateral, longitudinal, and vertical dispersion, which are, in turn, a function of water depth (Fisher et al., 1979). Where dispersion is very low in one or more of these dimensions, the mixing of tributaries may be substantially constrained, resulting in stratification or other discontinuity. Interaction between channel geometry, inflow rates, and constrained mixing frequently results in obvious hydrologic bands or plumes when two water bodies meet. Examples include the confluence of rivers (Mertes, 1997; Moreira-Turcq et al., 2003), and plumes formed by rivers entering estuaries or oceans (Park et al., 1965; Nash & Moum, 2005; Thomas & Weatherbee, 2006). In natural channels, the depth is often the minimal dimension, and thus it is the vertical dimension that limits the magnitude of dispersion rates.

Here we describe an extreme example of hydrologic banding from a large river floodplain in California. These hydrologic bands are formed as floodwaters from four major tributaries successively spill into the floodplain, but do not mix substantially. Specific study questions included: (1) Over what range of flow conditions does banding occur? (2) How are the characteristics of the bands affected by different tributary inputs and floodplain geometry? (3) Are the observed banding phenomena consistent with basic theory about lateral dispersion? This information is intended to contribute to a better understanding of the conditions and mechanisms that result in hydrologic banding, and insight into the effects of over-bank flooding in marginal habitats.

Our study area was the Yolo Bypass, the primary floodplain of the lower Sacramento River, the largest tributary to the San Francisco Bay (Fig. 1). We became interested in the hydrology of the Yolo Bypass as part of fisheries and food web studies (Sommer et al., 2001a, b, 2004, 2005). The highly managed river has a mean annual discharge of about 800 $m^3 s^{-1}$ from a watershed of 70,000 km^2 (Schemel et al., 2004; Sommer et al., 2004). Yolo Bypass and its upstream counterpart, Sutter Bypass, convey flood flows of the Sacramento River and smaller tributaries around and away from cities such as the state capitol, Sacramento.

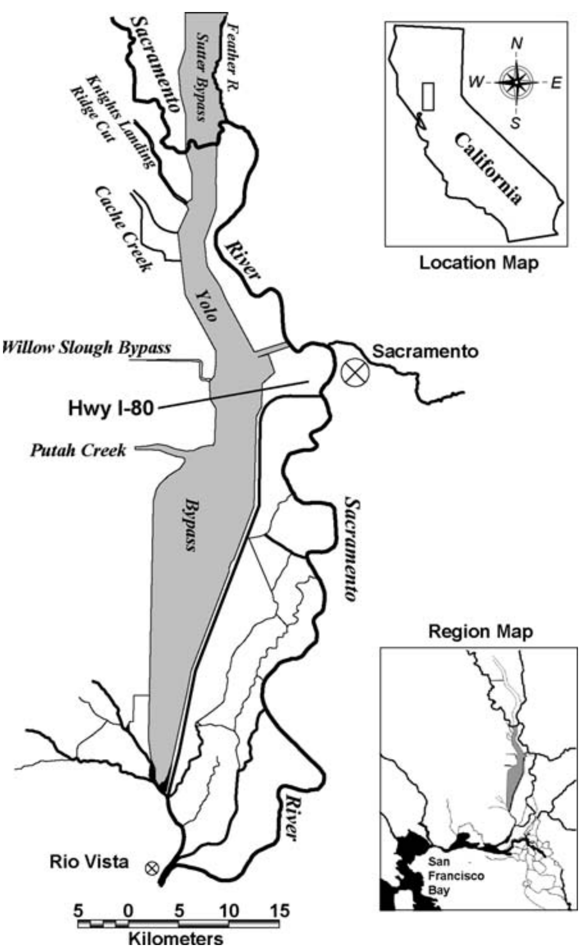

Fig. 1 Location of Yolo Bypass and its tributaries in relation to the San Francisco Estuary. The San Francisco Estuary represents the region from San Francisco Bay upstream to Sacramento

The Yolo Bypass is inundated from the Sacramento River during parts of winter and spring, in about 70% of years, when total flow in the Sacramento exceeds 2,000 $m^3 s^{-1}$ at the northern boundary of the Yolo Bypass. Flow also enters the Yolo Bypass from small streams on its western margin including Knights Landing Ridge Cut, Cache Creek, and Putah Creek. At peak flows, up to 24,000 ha of the 61 km long, partially-leveled floodplain is inundated. Typical dimensions are 2–10 km wide, with a mean depth of 2 m or less. Floodwaters recede from the northern and western portions of the bypass into a perennial channel on the eastern edge of the Bypass, which drains back into the Sacramento River near Rio Vista.

Materials and Methods

The first step in our analysis was the development of a photomosaic of a March 2, 1998 flow event based upon a series of aerial images captured at a scale of 1:24,000. As will be described in further detail, this set of natural color aerial photographs showed prominent and distinct hydrologic bands for each of the four major tributaries: Sacramento River, Knights Landing Ridge Cut, Cache Creek, and Putah Creek. To address our first study question, the persistence of this phenomenon over a range of hydrological conditions, we examined additional historical images of the floodplain. The aerial images included black and white photographs, color photographs, and NASA MODIS satellite imagery. The scale of the images varied from 1:3,000 to 1:24,000. Each set of images covered most of the lower Yolo Bypass, but not necessarily the entire length of the floodplain. For each set of images, we determined whether each of the four major tributary bands were present. The quality of the aerial photographs varied, so the absence of given tributary band did not necessarily mean that it was not present, only that we could not detect a distinct band. The total floodplain flow during each observation (and in the analyses described below) was obtained from California Department of Water Resources (http://www.iep/dayflow/index.html).

Our second study question was to evaluate how the hydrologic bands were affected by different tributary inputs and floodplain geometry. We examined this by measuring mean width of tributary bands for two sets of aerial photographs under two very different flow conditions. One set of images was the previouslydescribed March 2, 1998 flood event in which all four tributaries flowed into the Yolo Bypass, and the other was a March 18, 1998 event in which only Putah Creek and Cache Creek provided substantial inflow. For each set of images, the width of each tributary band was measured from 13 west–east transects drawn at 1 km intervals below the mouth of Putah Creek, the point at which all four bands were possible. We applied simple linear regression to the transect data to test the hypothesis that the width of each band was proportional to the total inundated width of the floodplain. We examined whether tributary flow had a clear effect on tributary band width by comparing the mean band widths and flow inputs levels for the two sets of images.

In order to address our third study question, we used a simple model to evaluate whether the observed banding phenomenon was consistent with hydrodynamic theory. We reasoned that dispersion theory provides a useful framework in which to explain the persistent observed flow bands (Fischer et al., 1979). The concentration of a constituent introduced at a point source upstream can be modeled as a Gaussian (bell-curve) distribution downstream. The same approach can be applied to the boundary between two flows, in which the initially sharp boundary between two tributary bands mixes and becomes more diffuse, again following a Gaussian distribution. The width of a spreading plume from a point source is analogous to the standard deviation in a normal distribution, according to the Fisher et al., (1979) transverse mixing formula

$$\text{width} = 4\sigma$$

where σ is standard deviation of the concentration distribution. This, in turn is a function of a transverse dispersion coefficient, K_t; the distance downstream, x; and the mean flow velocity, u_m:

$$\sigma = \sqrt{2K_t x/u_m} \tag{1}$$

Note that the term (x/u_m) has units of time, thus equating distance traveled with dispersal time. Experiments have found that in cases of open channel flow such as the Yolo Bypass, the rates of vertical, lateral, and longitudinal dispersion are often expressed as a direct function of channel depth in the form (Fischer et al., 1979):

$$K_t = \alpha\, du^* \tag{2}$$

where K_t is the lateral dispersion coefficient, α is a unitless coefficient estimated from field observations, approximately equal to 0.15; d is depth, and u^* is the shear velocity,

$$u^* = \sqrt{gdS} \tag{3}$$

where g is gravitational acceleration; and S is water surface slope.

Hence, our approach was to measure 4σ, the observed width of dispersion (i.e., boundary area) in adjacent bands in the March 2, 1998 set of aerial photographs, and to compare the measurements to modeled dispersion widths. For the theoretical model, we used typical input variables that have been estimated for Yolo Bypass (e.g., Sommer et al., 2004): $S = 1.4 \times 10^{-4}$, $d = 2$ m, $x = 34{,}000$ m, $u_m = 0.24$ m/s.

Results

Our initial photo mosaic showed prominent hydrologic bands along the entire 61 km length of the Yolo Bypass (Figs. 2 and 3). The hydrologic bands are formed as floodwaters from the Sacramento River, Knight's Landing Ridge Cut, Cache, and Putah creeks (visible respectively as bands from east to west) successively spill into the Yolo Bypass, but do not mix until at least the southern base of the floodplain. Similar bands have also been observed upstream in the Sutter Bypass (May 25, 2005 Landsat images; M. Kirkland, unpublished data).

Inspection of historical aerial photographs taken during the past four decades suggested that three or four tributary bands are typically present at all but the lowest flow levels (Table 1). These hydrologic bands were present at flow levels ranging from 1.5 year recurrence event (March 18, 1998) to 48 year recurrence event (February 20, 1986). Analysis from two of the 1998 images indicates the width of each band is correlated with the width of the floodplain during each flood event (Fig. 4). The relationships between the width of each tributary and total floodplain width were all statistically significant at the <0.05 level based on simple linear regression. However, band width is not proportional to the amount of flow from each tributary (Table 2). For example, the width of the Putah Creek band was much wider than would be expected based on its modest inflow during each flow event. The reason is that the floodplain slopes from west to east, so the westernmost bands occur in

Fig. 2 Natural color photomosaic of the 61 km Yolo Bypass floodplain during a March 1998 flood event

Fig. 3 Higher resolution photomosaic of the central 10-km of the Yolo Bypass during a March 1998 flood event. Some digital retouching was performed to smooth the transitions among the individual photos used to generate the mosaic

shallower water, where a given volume of water will inundate a larger area. The band width is also not proportional to inflow levels among flow events. For example, the Putah Creek band was wider at a flow level of 22 $m^3 s^{-1}$ (March 18, 1998) than it was at a flow level of 127 $m^3 s^{-1}$ (March 2, 1998).

Examination of the Fig. 3 aerial photographs produced observed widths of the dispersion regions (e.g., boundary area) between bands of between 150 and 450 m. Using typical values for the Yolo Bypass our simple hydrodynamic model produced a predicted dispersion region (4σ) of $\sim$270 m. On the basis of this framework, the observed dispersion rates agree well with theory.

Discussion

The Yolo Bypass banding phenomenon is notable for several reasons. First, the number of tributaries involved is relatively large. While there are many examples of minimal mixing by two water sources (Mertes, 1997; Moreira-Turcq et al., 2003), Yolo Bypass is the only case we are aware of where at

Table 1 Presence of distinct tributary bands captured in historical aerial photographs or satellite images of Yolo Bypass

Date of image capture	Putah Creek	Cache Creek	Knights Landing Ridge Cut	Sacramento River	Peak total floodplain flow (m^3 s^{-1})	Images[a,b]
1/22/1970	Yes	Yes	Yes	Yes	5,533	B,0
1/2/1974	No	Yes	Yes	Yes	774	B,1
1/20/1978	Yes	Yes	Yes	Yes	1,821	B,3
3/8/1983	Yes	Yes	Yes	Yes	4,790	B,2
2/20/1986	No	Yes	Yes	No	14,130	B,2
2/22/1986	No	Yes	Yes	Yes	8,901	B,2
2/24/1986	No	Yes	Yes	Yes	5,748	B,2
3/5/1986	Yes	Yes	Yes	Yes	824	B,2
1/15/1995	Yes	Yes	Yes	Yes	3,368	B,2
3/2/1998	Yes	Yes	Yes	Yes	1,039	C,4
3/18/1998	Yes	Yes	Low inflow	No inflow	152	C,4
2/28/2004	Yes	Yes	No	Yes	2,980	S
3/7/2004	No	Yes	No	Yes	897	S
1/4/2006	Yes	Yes	No	Yes	7,330	S
1/9/2006	No	Yes	No	Yes	2,466	S

[a] Image type: B = black and white; C = color; S = NASA MODIS satellite

[b] Scale: 0 = Oblique images; 1 = 1:3,000; 2 = 1:12,000; 3 = 1:18,000; 4 = 1:24,000

least four relatively unmixed tributary bands are routinely observable. Similarly, while hydrologic banding at the confluence of two rivers, or where rivers meet estuaries is fairly common, examples involving tributaries within a floodplain are less well documented (Mertes, 1997). Third, the 61 km distance over which the bands remain unmixed is relatively long. In addition, the wide flow range under which hydrologic banding was observed (Table 1) suggests that this is a persistent feature independent of flow magnitude, and complete mixing of tributaries has not been observed.

The fact that the Yolo Bypass tributary bands remain largely unmixed despite major constrictions is, at first glance, surprising (Yee and Biltoft, 2004). Approximately half way down the Yolo Bypass are an elevated vehicle causeway and a railway raised track bed ("Hwy I-80" in Fig. 1), which laterally constrains substantial portions of flow. As the floodplain narrows near its southern end, there is also a major peninsula of higher ground that suddenly reduces the width of the floodplain by at least 50%. Both types of obstructions might be expected to substantially increase lateral dispersion. In fact, the bands narrow to negotiate these constrictions, but are not appreciably mixed while doing so.

An additional factor that should promote lateral mixing is wind-driven shear due to long wind fetch across the floodplain. The prevailing winds in the Yolo Bypass are either northwest or southwest, frequently creating a wind fetch of 10 km or more. However, several mechanisms act to make wind driven flow small relative to mean longitudinal flow. First, while prevailing winds are generally perpendicular to the main flow, mean wind speed is generally moderate, $\sim$2.5 m s^{-1}. Surface wind drift is on the order of 3% of wind speed (Horne and Goldman, 1994), but this surface flow is a small fraction of the water column, making lateral transport even smaller relative to longitudinal flow (Smith, 1991). Second, turbulent vertical flow will tend to homogenize any vertical differences. Third, flow structures such as Langmuir spirals will be constrained to length scales on the order of the shallow depth.

Despite these potential sources of lateral mixing, our simple model suggests that the observed low dispersion rates are reasonable based on hydrodynamic theory. In particular, key features of Yolo Bypass that contribute to the lack of mixing include shallow depth and low gradient. Mean floodplain depth mostly remains less than two meters to at least

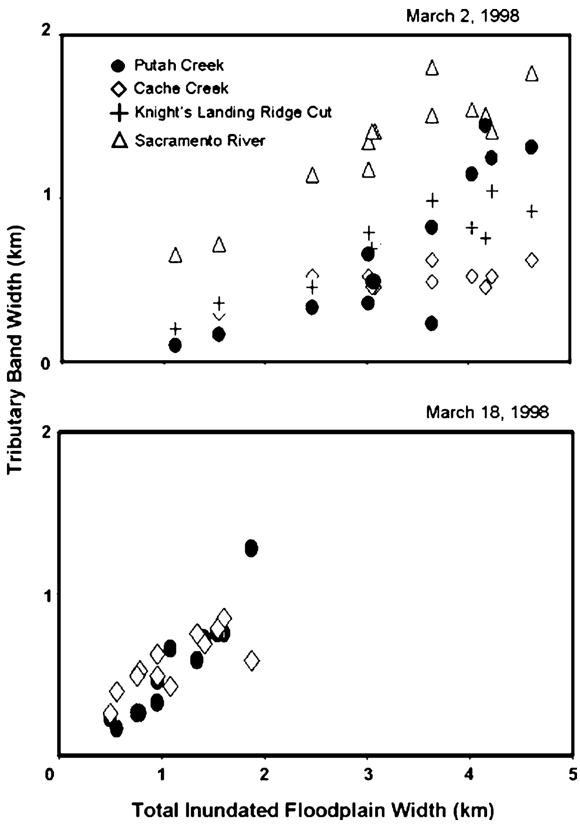

Fig. 4 Relationships between tributary band width (km) and total inundated floodplain width (km) for two sets of aerial images. The relationships between the width of each tributary and total floodplain width are statistically significant at the <0.05 level based on simple linear regression for each set of figures

7,100 $m^3\ s^{-1}$ total flow (Sommer et al., 2004, 2005). Floodwaters recede from the northern and western portions of the bypass along relatively even and modest 0.01% north–south, 0.09% west–east slope. Within the theoretical framework, the small depth compared to channel width, low slope, and low velocity combine to produce very low transverse dispersion rates and therefore very restricted mixing between tributary bands. The forms of the equations imply that the dispersion rate in a floodplain will vary gradually with changes in the input variables. The fact that most of Yolo Bypass has low profile vegetation likely contributes to low mixing levels between the bands. Habitat in the Yolo Bypass is predominantly low annual vegetation (managed wetlands, agriculture), except at the base of the floodplain, a lake with light tule (*Scirpus*) marsh around its perimeter. These habitat types present low surface roughness, reducing vertical and lateral shear flow dispersion. Like other floodplains, Yolo Bypass experiences variation in the timing of flooding from different tributaries (Schemel et al., 2004), a feature that has been proposed to maintain hydrologic heterogeneity (Mertes, 1997). However, the timing of regional storms generally produce coincident flows from most of the tributaries named above, and timing alone would not be sufficient to maintain the flow bands.

The low rate of lateral mixing of different water sources appears to be a general pattern in floodplain habitat (Mertes, 1997). However, the chemical and biological consequences of reduced tributary mixing are not well understood. In other incompletely mixed aquatic habitats, tributaries or plumes result in substantial variability in water chemistry (Park et al., 1965). This is likely the case in Yolo Bypass, as Schemel et al. (2004) found that each of the Yolo Bypass tributaries had distinct chemical properties. Cache Creek is the primary source of mercury and methyl mercury to the San Francisco estuary

Table 2 Mean width (km) of tributary bands for two sets of aerial photographs. The percent of total floodplain width is shown in parentheses. Flow levels (m3 s^{-1}) are also shown for each tributary along with their percent contribution to total flow (in parentheses)

	Putah Creek	Cache Creek	Knights Landing Ridge Cut	Sacramento River	Total
March 2, 1998					
Flow	127 (12.2%)	241 (23.2%)	680 (65.5)[a]	680 (65.5)[a]	1038 (100)
Band width	0.68 (21.1%)	0.48 (14.9%)	0.71 (22.1%)	1.34 (41.8)	3.2 (100)
March 18, 1998					
Flow	14.2 (48.4%)	85.8 (51.6%)	0 (0%)	0 (0%)	152 (100)
Band width	1.6 (48.4%)	1.8 (51.6%)	0 (0%)	0 (0%)	3.4 (100)

[a] Since there was no stream gauging data for Knights Landing Ridge Cut, its combined flow with the Sacramento River is shown

(Domagalski, 2001), suggesting that the western half of the Yolo Bypass may experience increased mercury loading, since the Cache Creek tributary band typically occurs there.

Floodplains are widely recognized to be important components of aquatic ecosystems (Junk et al., 1989; Welcomme et al., 1979). Overbank flows that inundate seasonal floodplain enhance the production and diversity of fish, invertebrates, and phytoplankton in many regions, thereby subsidizing riverine ecosystems. As noted by Mertes (1997) partial mixing probably creates unique ecotones within floodplains. Banding creates distinct and persistent biogeochemical conditions in geographically close proximity. In Yolo Bypass, the hydrologic banding phenomenon is likely to be important for migrating adult Chinook salmon, which pass through the floodplain on their journey to spawn in the upstream channels of Putah Creek, the mainstem Sacramento River, and its tributaries (Harrell and Sommer, 2003). Since salmon rely on chemical cues to migrate upstream, the photographs provide clues as to the likely routes. Moreover, inundation of the Yolo Bypass creates one of the major rearing habitats for downstream migrating juvenile Chinook salmon, which take advantage of rearing areas created by seasonally inundated vegetation and an enriched food web in the floodplain (Sommer et al., 2001a, b, 2004, 2005).

Acknowledgements This study was performed as part of the Interagency Ecological Program with funding from the CALFED Bay-Delta Program. The manuscript was improved by analyses by Chris Enright, and Xiaochun Wang, and comments by Marianne Kirkland and two anonymous reviewers. Cindy Messer and Gina Benigno assisted with interpretation of the aerial photographs.

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